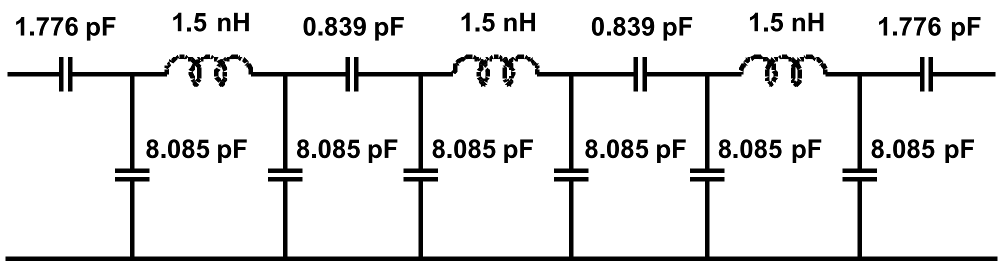
for "Embedded Passive Update" column, CircuiTree, March 2005

Sizing an Embedded Bandpass Filter

Rick Ulrich

I've been working for some weeks with Symmorphix Inc. of Sunnyvale on a project to demonstrate RF filters using embedded passives. This is not a journal article so I'll skip lots of details, but we learned a few things about in general, and I thought I'd share some of them here. The demo filter was a 1.9 to 2.0 GHz bandpass as shown below:



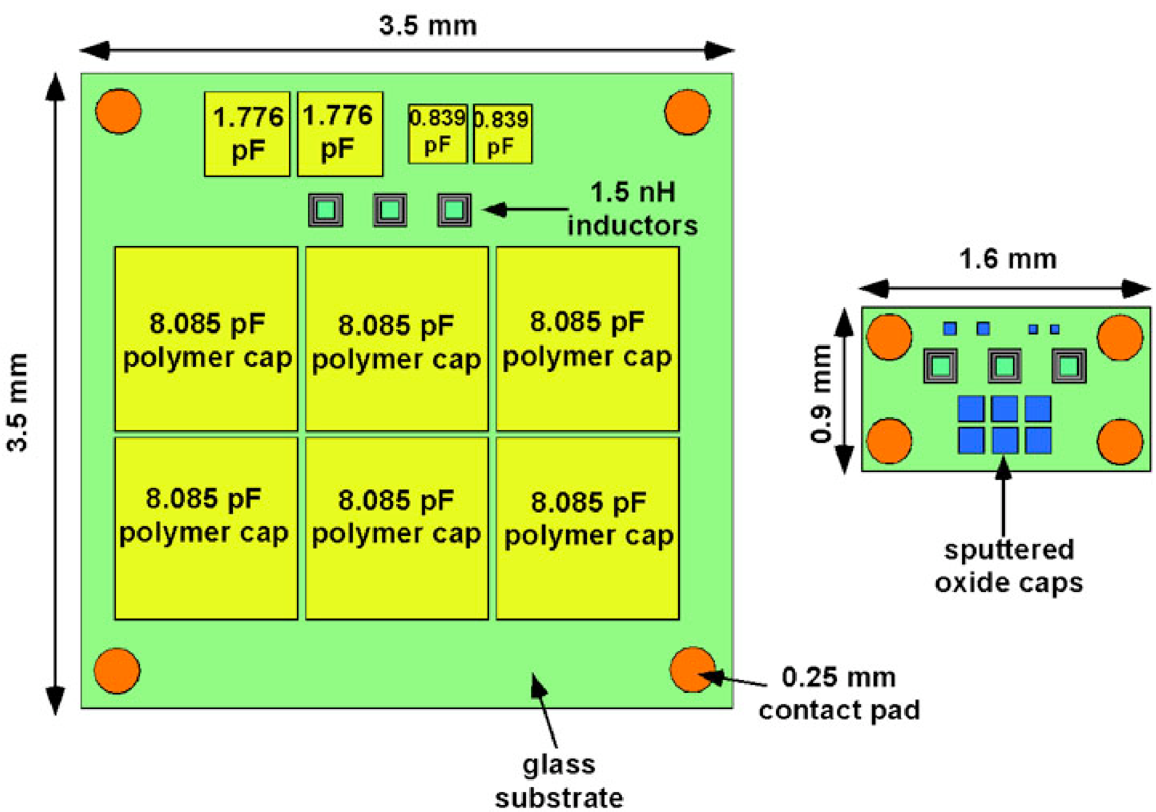
The first thing to notice is that it's ripe for embedding. The L and C values are close to the bottom of the range for consumer equipment and lower values can be embedded with higher yield, better reliability, and, of course, smaller footprint. To be an economical design, this whole thing needs to come in no larger than a few mm^2.

The value of the inductors are about a linear function of the linewidth (equals line spacing) if you keep the number of turns constant or is about a square function of number of turns if you keep linewidth and spacing constant. Using contact alignment on a glass substrate, 10 micron lines and spaces were feasible with good yield. To get a quick idea of the overall area, the inductors can be roughly sized using any one of several semi-empirical formulas. We have these in-house from old student projects, and there are plenty in the literature such as the Wheeler equation, the Mohan equation, the Hurley and Duffy equations, http://www-smirc.stanford.edu/spiralcalc.html, and many others. These indicated that we needed about 2.5 turns of 10 micron Cu with an OD of 0.190 mm to get 1.5 nH. Later, when run on a full-wave solver, this turned out to be accurate to within about 20%, not good enough for final design, but sufficient for initial layout. For a given required inductance, such as 1.5 nH, inductors can be scaled down almost without limit by using more turns with finer linewidths, but at the expense of lower Q. We used square inductors with a keep-away distance of about 1/3 an inductor radius so other metal won't interfere with the inductor's field.

For capacitors, there are four types of embeddable dielectrics:

- thin films (SiO_2, Si_3N_4, Al_2O_3, Ta_2O_5)
- unfilled polymers (epoxy, polyimide, FR4, BCB)
- ferroelectrics ($BaTiO_3$, PZT)
- ferroelectric-filled polymers($BaTiO_3$ in epoxy)

The last two are not as suitable for filter applications because their dielectric constants tend to drop significantly with frequency. This is less of an issue with ferro-filled polymers and could even be built into the filter's response, but it's just cleaner to use a well-behaved dielectric. Four mils of FR4 had such a low specific inductance, only 0.041 nF/cm^2, that the 8.085 pF caps would have been huge at over 4 mm on a side. The highest capacitance polymer we could make consisted of a few microns of BCB, which gave 0.80 nF/cm^2, but this still leaves the capacitors almost five times the diameter of the inductors. In order to keep either the inductors or the capacitors from dominating the design, we got Symmorphix to sputter half a micron of Ta_2O_5, which gave about 40 nF/cm^2, plenty to shrink the caps to about the size of the inductors. The cartoon below shows the relative sizes of the final filter using the two options for dielectrics. Although you never feel they are small enough, over seven thousand of these will fit on a 6" glass wafer.



The main lessons we learned were to use the smallest linewidth you can to minimize inductor size within whatever Q restraints you have, then select a dielectric to get the caps down to that scale. The smallest total form factor and easiest processing seemed to be achieved when neither the inductors nor the capacitors controlled the overall size. Semi-empirical equations for sizing inductors, those that can be done on a spreadsheet, work well for general sizing and layout, but a full-wave solver is needed to get within that last few percent. Another way is to fabricate dozens of different versions on one wafer and pick the one that performs the most like you want for the production masks. It can take some time to do the artwork on AutoCAD, but provides working prototypes on the first pass.